Tests of discrete symmetries in K systems

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K mesons – a 70 years history

1944: first indication of a new charged particle with mass ~0.5 GeV/c² in cosmic rays (Leprince-Ringuet, Lheritier)

1947: first K⁰ observation in cloud chamber - V particle (Rochester, Butler)

1955: introduction of Strangeness (Gell-Mann, Nishijima)
    K⁰, K bar⁰ are two distinct particles (Gell-Mann, Pais)

1955 prediction of regeneration of short-lived particle (Pais, Piccioni)

1956 Observation of long lived K_L (BNL Cosmotron)

1957 τ-θ puzzle on spin-parity assignment, P violation in weak interactions

1960: Δm = m_L - m_S measured from regeneration

1964: discovery of CP violation (Cronin, Fitch,…)

1970: suppression of FCNC, K_L→μμ - GIM mechanism/charm hypothesis

1972: Kobayashi Maskawa six quark model: CP violation explained in SM

1992- 2000: CPLEar: K⁰, K bar⁰ time evolution and decays, T, CP, CPT tests


2000-2006: KLOE at DaΦne: first Φ factory enters in operation, V_{us} and precision tests of the SM, entangled neutral K pairs and CPT and QM tests.
K mesons – a 70 years history.....

after 70 years from the first observation one might wonder whether investigations on kaons have exhausted the information that such relatively simple but rich system can provide:

I’ll try to convince you that this is not the case....
**Experimental kaon talks at DISCRETE 2014**

K. Massri: Precision tests of the Standard Model with kaon decays at CERN (Thursday, Parallel 4)

M. Lenti: ChiPT tests at NA48 and NA62 experiments at CERN (Thursday, Parallel 4)

D. Kamiska: Study of KS semileptonic decays and CPT tests with the KLOE detector (Thursday, Parallel 4)

F. Hahn: Prospects for K+ ->π+ nu nu observation at CERN in NA62 (Thursday, Parallel 4)

E. De Lucia: The KLOE-2 experiment at DAFNE (Thursday or Friday, to be announced)

A. Gajos : A direct test of T symmetry in the neutral K meson system at KLOE-2 (Tuesday, Parallel 1)
Next kaon experiments at hadron machines
Rare K decays: the full picture

Switch to quantitative test of the SM; Flavor sector probing extremely high energy scales: precision frontier complementary to LHC energy frontier
Some (tiny!) BRs can be computed to very high (few percent) precision
The $K \rightarrow \pi \nu \bar{\nu}$ decays in the Standard Model

<table>
<thead>
<tr>
<th>Decay (BR x $10^{10}$)</th>
<th>Theory (SM Prediction)</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
<td>$0.781 \pm 0.075 \pm 0.029$ [1]</td>
<td>$1.73 \pm 1.15 - 1.05$ [2]</td>
</tr>
<tr>
<td>$K^0 \rightarrow \pi^0 \nu \bar{\nu}$ (CPV)</td>
<td>$0.243 \pm 0.039 \pm 0.006$ [1]</td>
<td>$&lt; 260$ [3]</td>
</tr>
</tbody>
</table>

SM predictions are extremely clean

- Short Distance dynamics dominates:
  - FCNC processes only arising at loop level (Z penguins and box diagrams)
- Hadronic matrix element known from $K_{e3}$ semileptonic decays BR via isospin rotation
- Uncertainty dominated by CKM matrix elements
- Amplitude very well predicted:
  - clean $V_{td}$ dependence
  - the BR measurement determines $V_{td}$ without input from Lattice QCD ($\delta BR/BR \approx 10\% \rightarrow \delta V_{td}/V_{td} \approx 7\%$)
- Strongly suppressed in SM ($<10^{-10}$):
  - Key role in seeking NP beyond SM

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The $K \to \pi \nu \nu$ decays beyond the Standard Model

- Rare K decays are highly suppressed (CKM) $\rightarrow$ highly predictive for SM extensions
- Many SM extensions predict sizeable deviations from the $BR_{SM}$ value
- Possibility to distinguish among many different models:
  - Chargino/H$^\pm$ loops (MSSM at low/large $\tan\beta$), R-parity violation (non MFV), enhanced EW Penguins, Little Higgs, extra dimensions, 4th generation, ...

NP models predicting deviations from MFV:
- Randall-Sudrum,
- Littlest Higgs with $T$-parity,
- SM 4th generation

**Graphical Content**

- Excluded area
- Grossman-Nir bound
- MSSM $-\mathcal{A}_U$
- LHT
- SM4
- Experimental uncertainty
- MFV
- D. Straub
- CKM'10

**Equations**

$B(K^\pm \to \pi^\pm \nu \nu) \times 10^{11}$

$10^{10} \times BR(K^+ \to \pi^+ \nu \nu)$
$K^+ \rightarrow \pi^+ \nu \nu$ decay at NA62 - CERN

**NA62: Beam & Detectors**

Primary SPS beam: $p = 400$ GeV/c
- proton/pulse $3 \times 10^{12}$ ($\times 3$ NA48/2)
- duty cycle 4.8 s / 16.8 s

Secondary unseparated positive beam:
- $p_K = 75$ GeV/c ($\Delta p/p \sim 1.1\%$)
- $\pi/K/p (K^+ \sim 6\%$, positron free)
- $K^+$ decays / year $= 4.5 \times 10^{12}$ ($\times 45$ NA48/2)

Beam acceptance $= 12$ mstr ($\times 25$ NA48/2)
Area @ beam tracker $= 16$ cm$^2$
Integrated average rate $= 750$ MHz
Average rate @ detectors $\approx 10$ MHz

Vacuum at $10^{-6}$ mbar to reduce beam-gas interaction (use existing NA48 decay tank)

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**Diagram:**
- **Target**
- **CEDAR**
- **Gigatracker (GTK)**
- **CHANTI**
- **LAV:** Large Angle Photon Veto
- **CHOD:** Charged Hodoscope
- **SAV:** Small Angle Veto
- **Decay Region 65m**
- **Straw Tracker**
- **RICH**
- **Total Length 270m**
- **LKr**
- **MUV**

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P. Cenci BEACH 2012
NA62: guiding principles

- Kinematic rejection ($m^2_{miss}$):
  - Minimal amount of material budget:
    - $X/X_0$ kaon spectrometer (Gigatracker, Si pixel): 1.5% total
    - $X/X_0$ pion spectrometer (Straw Chambers in vacuum) < 2% total

- High efficiency photon veto:
  - $10^{-8} \pi^0$ veto inefficiency in $K^+ \rightarrow \pi^+\pi^0$ events
    - Offline analysis trick: $P_{\pi^+} < 35 \text{ GeV/c} \rightarrow E_{\pi^0} > 40 \text{ GeV}$
    - $10^{-5}$ LKr inefficiency for $E_\gamma > 10 \text{ GeV}$
    - Hermeticity up to 50 mrad and down to 500 MeV photons (LAV detectors)

- Precise timing for K-$\pi$ matching:
  - Gigatracker time resolution: < 200 ps / station
    (beam test results on a prototype)
  - RICH time resolution: < 80 ps [NIM A 593 2008]

- Particle ID
  - MUV and RICH for $\mu$-$\pi$ separation → totally independent ID methods
  - LKr and RICH for $\pi$-$e$ separation → totally independent ID methods
  - Cerenkov threshold counter on beam to control the beam induced background
K⁺ → π⁺νν decay at NA62 - CERN

GOAL: 10% precision measurement of BR(K⁺ → π⁺νν)

O(100) K⁺ → π⁺νν decays with ~10% background in 2 years data taking

Requirements:

Statistics:
- BR(SM) ~ 8 x 10⁻¹¹
- Acceptance: 10%
- K decays: ~10¹³

Systematics:
- ≥10¹² background rejection
- ~10% precision on background measurement

Present status:
- Installation completed
- First physics run SUCCESSFULLY started 6 weeks ago!
  - completing commissioning of hardware and readout;
  - lower intensity beam;
  - reach SM sensitivity
$K_L \rightarrow \pi^0 \nu \nu$ decay at KOTO - JPARC

KOTO aims to improve the sensitivity by 3 orders of magnitude (~3 SM events)
A. Di Domenico

DISCRETE 2014 – 2-6 December 2014, King’s College, London

30GeV Slow Extraction

T1 target

J-PARC
Hadron Hall

N

56m

KL beam line
(KL decay in flight)

K1.1BR beam line
(K+ decay at rest)

30GeV Slow Extraction

T1 target

014, King’s College, London

Dec. 6, 2012
$K_L \rightarrow \pi^0 \nu \nu$ decay at KOTO: experimental principle

Pencil beam & Two gammas and nothing

- Calorimeter and Hermetic veto
  - energy and position with small beam hole and in-beam detector
- Vertex reconstruction with pi0 mass and vtx on z-axis assumption
  - Fiducial region in z $\leftrightarrow$ neutron background
  - $\pi^0$ Pt reconstruction $\rightarrow$ High Pt selection

H. Nanjio CKM 2012
The KOTO experiment at JPARC

After the major Earthquake in Japan on 11 March 2011
(no damages to beam line and KOTO detector)
JPARC started re-commissioning on Dec.2011 and resumed operations
on Jan.2012

All detectors installed by May 2013
KOTO detector

CsI calorimeter + Hermetic veto system

We installed all detectors by May 2013.

Shiomi CKM2014
The KOTO experiment at JPARC

After the major Earthquake in Japan on 11 March 2011 (no damages to beam line and KOTO detector) JPARC started re-commissioning on Dec.2011 and resumed operations on Jan.2012

All detectors installed by May 2013

KOTO first physics run: May 17 2013
- beam power: 24 kW (10% of design intensity)
- Unfortunately, the data taking was terminated after only 100 hours due to a radiation accident in J-PARC Hadron hall (gold target partially melted and radioactive material diffused in the atmosphere)
Preliminary analysis of the data (100h run)

EVENTS OUTSIDE THE SIGNAL BOX

\( P_t \) vs \( Z \) distribution after applying **loose** selection cuts

We understand the events outside the signal box well.
Preliminary analysis of the data (100h run)

OPENING THE SIGNAL BOX

- One event was observed inside the signal box.
- $N_{\text{obs}}$ is consistent with $N_{\text{exp}}$ statistically

This result corresponds to a single event sensitivity of $1.3 \times 10^{-8}$ (nearly the same as in E391a: $1.1 \times 10^{-8}$)
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- Unfortunately, the data taking was terminated after only 100 hours due to a radiation accident in J-PARC Hadron hall
  (gold target partially melted and radioactive material diffused in the atmosphere)
- nearly the same sensitivity of E391a has been achieved with only 100 h run (instead of ~1000 h), turning it in a SUCCESS!
- the next run is expected to start beginning 2015 with the goal: improve background suppression (new detectors, improved analysis methods) reach higher sensitivity (x 20) wrt the first run.
**TREK experiment**

*Transverse $\mu^+$ polarization* in $K^+\rightarrow\pi^0\mu^+\nu$ decay

Search for a non zero T-odd observable

Pseudo-TRV due to FSI effects low ($\sim 10^{-6}$)

**KEK E246** experiment (final 2006):

$$P_T = -0.0017 \pm 0.0023 \pm 0.0011$$

$$P_T < 5 \cdot 10^{-3} \ (90\% \ CL)$$

TREK experiment Goal:

$$\sigma(P_T) \approx 10^{-4} \text{ in 1 year}$$

**E36/TREK** on K1.1BR beam.

The JPARC E36/TREK experiment aims to measure $R_K$ and reduce the error by $x2$.

$$R_K = \frac{\Gamma(K^+ \rightarrow e^+\nu)}{\Gamma(K^+ \rightarrow \mu^+\nu)}$$

Physics run of E36 in Spring 2015
TREK experiment

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**Physics run of E36 in Spring 2015**
Rare $K_S$ decays at LHCb

$K_S \rightarrow \mu^+\mu^-$

FCNC family:
SM prediction $B(K_S^0 \rightarrow \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$

Normalisation:

$$\frac{B(K_S^0 \rightarrow \mu^+\mu^-)}{B(K_S^0 \rightarrow \pi^+\pi^-)} = \frac{\epsilon_{\pi\pi} N_{K_S^0 \rightarrow \mu^+\mu^-}}{\epsilon_{\mu\mu} N_{K_S^0 \rightarrow \pi^+\pi^-}}$$

We measure with $1.0 \text{ fb}^{-1}$:

$B(K_S^0 \rightarrow \mu^+\mu^-) < 11(9) \times 10^{-9}$

This limit is a factor 30 below the previous measurement!

with the upgrade -> precision of $O(10^{-10})$

Considering to study also other decays: $K_S \rightarrow e\epsilon\epsilon\mu$, $eeee$, $\pi^0\epsilon\mu$

LHCb is not designed for kaon physics but might contribute thanks to the copious production of kaons at LHC and the excellent reconstruction capabilities; cons: huge background to fight, and trigger limitations.
The Protvino project

SPHINX+GAMS+ISTR A → OKA at Protvino:
65-70 GeV $10^{13}$ ppp at U-70 (38% DC)
12.5 GeV RF-separated $K^+$ beam $5 \cdot 10^6$ Kpp ($K/\pi \approx 4$)
Commissioning beam and detector with runs started 2009
10-100x improvement on ISTRA Kaon program + spectroscopy
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The Fermilab plan

Unfortunately the ORKA experiment in particular and kaon physics research more broadly has been terminated at Fermilab for the foreseeable future
next kaon experiment experiment at e+e- collider with entangled kaons
KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:
- new scheme of the interaction region (crabbed waist scheme) at DAΦNE (proposal by P. Raimondi)
- increase L by a factor $\times 3$ demonstrated by an experimental test

KLOE-2 experiment:
- extend the KLOE physics program at DAΦNE upgraded in luminosity
- Collect $O(10) \text{ fb}^{-1}$ of integrated luminosity in the next 2-3 years

Physics program
(see EPJC 68 (2010) 619-681)
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare $K_S$ decays
- $\eta, \eta'$ physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, $a_\mu$
- Dark forces: search for light U boson

Detector upgrade:
- $\gamma\gamma$ tagging system
- inner tracker
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)
DAΦNE luminosity upgrade

- DAΦNE upgrade (2008): new interaction scheme; large beam crossing angle + crabbed waist sextupoles
- In the last years a large consolidation and maintenance program of the machine has been carried out.
- Commissioning of DAFNE and new KLOE-2 detectors started in Jan. 2014, and after two major stops, (e.g. interruption of water supply from the Roman Aqueduct!) is rapidly progressing.

- November 2014:
  - one week after restarting collisions
  - **Best peak luminosity:** $L = 1.8 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - Improved background conditions
  - Stable machine operation
  - Goals:
    - collect $\sim 1 \text{ fb}^{-1}$ of good data by mid 2015
    - $O(10 \text{ fb}^{-1})$ in the next 2-3 years
**KLOE-2 at DAFNE**

- **Calorimeter System**
  - EMC - Lead / Scintillating Fibers w/ PMT Barrel and Endcaps
  - LET / LYSO+SiPMs
  - HET / Scintillator+PMTs
  - QCAL - Tungsten / Scintillating Tiles w/ SiPM
  - CCAL - LYSO Crystal w/ SiPM - Low-beta

- **Tracking System**
  - DC - Drift Chamber
    - 4 m x 3.3 m
  - Inner Tracker - 4 Cylindrical GEM detectors

- **Superconductive Magnet**
  - 0.52 T solenoidal field

- **Physics program** [EPJC 68 (2010)]
  - Kaon, eta, eta_s rare decays
  - Quantum interferometry
  - Dark photon search

Direct test of Time Reversal symmetry with neutral kaons

• EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-(K_1, K_2)$

$$
|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle|\bar{K}^0(-\bar{p})\rangle - |\bar{K}^0(\bar{p})\rangle|K^0(-\bar{p})\rangle \right]
$$

$$
= \frac{1}{\sqrt{2}} \left[ |K_+(\bar{p})\rangle|K_-(\bar{p})\rangle - |K_-(\bar{p})\rangle|K_+(\bar{p})\rangle \right]
$$

• decay as filtering measurement
• entanglement -> preparation of state
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\[ reference\ process \]

\[ 3\pi^0 \]
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• decay as filtering measurement
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$$|i\rangle = \frac{1}{\sqrt{2}} \left[ |K_+ (\bar{p})\rangle |K_- (-\bar{p})\rangle - |K_- (\bar{p})\rangle |K_+ (-\bar{p})\rangle \right]$$

reference process

$$K^0 \rightarrow K_-$$
EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$ ($K_1$, $K_2$)

$|i\rangle = \frac{1}{\sqrt{2}} \left[ |K_0(\bar{p})\rangle |\bar{K}_0(-\bar{p})\rangle - |\bar{K}_0(\bar{p})\rangle |K_0(-\bar{p})\rangle \right]$ 

$= \frac{1}{\sqrt{2}} \left[ |K_+(\bar{p})\rangle |K_-(\bar{p})\rangle - |K_-(\bar{p})\rangle |K_+(\bar{p})\rangle \right]$

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Direct test of Time Reversal symmetry with neutral kaons
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\]

- decay as filtering measurement
- entanglement -> preparation of state

\[3\pi^0\]

Note: CP and CPT conjugated process

\[\bar{K}^0 \rightarrow K_- \quad K_- \rightarrow \bar{K}^0\]

\[K^0 \rightarrow K_- \quad T\text{-conjugated process}\]

\[K_- \rightarrow K^0\]

A. Di Domenico

DISCRETE 2014 – 2-6 December 2014, King’s College, London
Direct test of Time Reversal symmetry with neutral kaons

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|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle |\bar{K}^0(-\bar{p})\rangle - |\bar{K}^0(\bar{p})\rangle |K^0(-\bar{p})\rangle \right] \\
= \frac{1}{\sqrt{2}} \left[ |K_+(\bar{p})\rangle |K_-(\bar{p})\rangle - |K_-(\bar{p})\rangle |K_+(\bar{p})\rangle \right]
\]

• decay as filtering measurement
• entanglement -> preparation of state

\[ I(\pi\pi, l^+; \Delta t) = C(\pi\pi, l^+) \times P[K_-(0) \rightarrow K^0(\Delta t)] \]

In general with $f_{\bar{X}}$ decaying before $f_Y$, i.e. $\Delta t>0$:

\[ I(f_{\bar{X}}, f_Y; \Delta t) = C(f_{\bar{X}}, f_Y) \times P[K_X(0) \rightarrow K_Y(\Delta t)] \]

with

\[ C(f_{\bar{X}}, f_Y) = \frac{1}{2(\Gamma_S + \Gamma_L)} |\langle f_{\bar{X}} | T | \bar{K}_X \rangle \langle f_Y | T | K_Y \rangle|^2 \]
Direct test of Time Reversal symmetry with neutral kaons

**T symmetry test**

<table>
<thead>
<tr>
<th>Reference Transition</th>
<th>Reference Final state</th>
<th>$T$-conjugate Transition</th>
<th>$T$-conjugate Final state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{K}^0 \rightarrow K_-$</td>
<td>$(\ell^+, \pi^0 \pi^0 \pi^0)$</td>
<td>$K_- \rightarrow \bar{K}^0$</td>
<td>$(\pi^0 \pi^0 \pi^0, \ell^-)$</td>
</tr>
<tr>
<td>$K_+ \rightarrow K^0$</td>
<td>$(\pi^0 \pi^0 \pi^0, \ell^+)$</td>
<td>$K^0 \rightarrow K_+$</td>
<td>$(\ell^-, \pi \pi)$</td>
</tr>
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<tr>
<td>$K_- \rightarrow K^0$</td>
<td>$(\pi \pi, \ell^+)$</td>
<td>$K^0 \rightarrow K_-$</td>
<td>$(\ell^-, \pi \pi)$</td>
</tr>
</tbody>
</table>

One can define the following ratios of probabilities:

\[
R_1(\Delta t) = \frac{P[K^0(0) \rightarrow K_+(\Delta t)]}{P[K_+(0) \rightarrow K^0(\Delta t)]} \\
R_2(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]} \\
R_3(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_+(\Delta t)]}{P[K_+(0) \rightarrow \bar{K}^0(\Delta t)]} \\
R_4(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]} .
\]

Any deviation from $R_i=1$ constitutes a violation of $T$-symmetry

*J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102*
Direct test of Time Reversal symmetry with neutral kaons

Any deviation from $R_i=1$ constitutes a direct evidence of T-symmetry violation

$$R_i(\Delta t=0)=1$$

$$R_2(\Delta t>>\tau_S)=1-4\text{Re}(\varepsilon)$$

$$R_4(\Delta t>>\tau_S)=1+4\text{Re}(\varepsilon)$$
Direct test of Time Reversal symmetry with neutral kaons

\[ R_1^{\exp} (\Delta t) = \frac{I(\ell^-, \pi \pi; \Delta t)}{I(3\pi^0, \ell^+; \Delta t)} = R_1(\Delta t) \times \frac{C(\ell^-, \pi \pi)}{C(3\pi^0, \ell^+)} \]

\[ R_2^{\exp} (\Delta t) = \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi \pi, \ell^+; \Delta t)} = R_2(\Delta t) \times \frac{C(\ell^-, 3\pi^0)}{C(\pi \pi, \ell^+)} \]

\[ R_3^{\exp} (\Delta t) = \frac{I(\ell^+, \pi \pi; \Delta t)}{I(3\pi^0, \ell^-; \Delta t)} = R_3(\Delta t) \times \frac{C(\ell^+, \pi \pi)}{C(3\pi^0, \ell^-)} \]

\[ R_4^{\exp} (\Delta t) = \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi \pi, \ell^-; \Delta t)} = R_4(\Delta t) \times \frac{C(\ell^+, 3\pi^0)}{C(\pi \pi, \ell^-)} \]

In practice two measurable ratios with \( \Delta t < 0 \) or >0

\[ R_2^{\exp} (-\Delta t) = \frac{1}{R_3^{\exp} (\Delta t)} = \frac{1}{R_3(\Delta t)} \times \frac{C(3\pi^0, \ell^-)}{C(\ell^+, \pi \pi)}, \]

\[ R_4^{\exp} (-\Delta t) = \frac{1}{R_1^{\exp} (\Delta t)} = \frac{1}{R_1(\Delta t)} \times \frac{C(3\pi^0, \ell^+)}{C(\ell^-, \pi \pi)}. \]
Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb$^{-1}$
Direct test of Time Reversal symmetry with neutral kaons

toy MC with $L=10$ fb$^{-1}$
Direct test of Time Reversal symmetry with neutral kaons

toy MC with $L=10 \text{ fb}^{-1}$
Direct test of Time Reversal symmetry with neutral kaons

Modifications due to direct CP violation effects have to be evaluated (release of the orthogonality condition of $K_+, K_-$), they could spoil the significance of the $T$ test.
Direct test of Time Reversal symmetry with neutral kaons

toy MC with $L=10 \text{ fb}^{-1}$
Direct test of Time Reversal symmetry with neutral kaons

toy MC with $L=10$ fb$^{-1}$

$R_2(\Delta t>>\tau_S)=1-4\text{Re}(\varepsilon) \sim 0.993$

$R_4(\Delta t>>\tau_S)=1+4\text{Re}(\varepsilon) \sim 1.007$
Direct test of Time Reversal symmetry with neutral kaons

Integrating in a $\Delta t$ region between 0 and 300 $\tau_S$ =>
stat. significance of 4.4, 6.2, 8.8 $\sigma$ with $L=5, 10, 20$ fb$^{-1}$ (full efficiency)

pros:
in the “plateau” region the impact of direct CP violation effects on the assumption of orthogonality of K+ and K- states has been evaluated => negligible

cons:
in the “plateau” region one needs to measure the absolute value of $R_i$.
Assuming no CPT violation in semileptonic decays:

$$\frac{C(\ell^{-}, 3\pi^0)}{C(\pi\pi, \ell^{+})} \sim \frac{C(\ell^{+}, 3\pi^0)}{C(\pi\pi, \ell^{-})} \sim \frac{BR(K_L \rightarrow 3\pi^0)}{BR(K_S \rightarrow \pi\pi)} \frac{\Gamma_L}{\Gamma_S} \equiv D.$$  

$$R_2(\Delta t) = \frac{R_2^{\exp}(\Delta t)}{D},$$

$$R_4(\Delta t) = \frac{R_4^{\exp}(\Delta t)}{D}.$$

- It is needed to measure the constant D with $\sim$ 0.1% precision, i.e. BRs and $K_S, K_L$ lifetimes
- in the “plateau” region effect proportional to Re($\varepsilon$)

**T test could be feasible at KLOE-2 @ DAΦNE with L=O(10 fb$^{-1}$)**
Direct test of Time Reversal symmetry with neutral kaons

CPT symmetry test

<table>
<thead>
<tr>
<th>Reference Transition</th>
<th>Decay products</th>
<th>CPT-conjugate Transition</th>
<th>Decay products</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0 \rightarrow K_+$</td>
<td>$(\ell^-, \pi\pi)$</td>
<td>$K_+ \rightarrow \bar{K}^0$</td>
<td>$(3\pi^0, \ell^-)$</td>
</tr>
<tr>
<td>$K^0 \rightarrow K_-$</td>
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<tr>
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<td>$(\pi\pi, \ell^+)$</td>
</tr>
</tbody>
</table>

One can define the following ratios of probabilities:

\[
R_{1,CP_T}(\Delta t) = \frac{P [K^0(0) \rightarrow K_+(\Delta t)]}{P [K_+(0) \rightarrow \bar{K}^0(\Delta t)]}
\]

\[
R_{2,CP_T}(\Delta t) = \frac{P [K^0(0) \rightarrow K_-(\Delta t)]}{P [K_-(0) \rightarrow \bar{K}^0(\Delta t)]}
\]

\[
R_{3,CP_T}(\Delta t) = \frac{P [\bar{K}^0(0) \rightarrow K_+(\Delta t)]}{P [K_+(0) \rightarrow K^0(\Delta t)]}
\]

\[
R_{4,CP_T}(\Delta t) = \frac{P [\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P [K_-(0) \rightarrow K^0(\Delta t)]}
\]

Any deviation from $R_{i,CP_T}=1$ constitutes a violation of T-symmetry

J. Bernabeu, A.D.D. in preparation
Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
$\text{Re}(\delta) = 3.3 \times 10^{-4}$  $\text{Im}(\delta) = 1.6 \times 10^{-5}$

toy MC with $L = 10 \text{ fb}^{-1}$
Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
Re(δ)=3.3 \times 10^{-4} \quad \text{Im}(δ)=1.6 \times 10^{-5}

\begin{align*}
R_{2,\text{CPT}} & \quad R_{2,\text{CPT}}^{\text{exp}}/D_{\text{CPT}} \\
R_{4,\text{CPT}} & \quad R_{4,\text{CPT}}^{\text{exp}}/D_{\text{CPT}}
\end{align*}

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Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with

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Modifications due to direct CP violation effects have to be evaluated (release of the orthogonality condition of \( K_+ \), \( K_\pm \)), they could spoil the significance of the T test.
Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
Re(δ)=3.3 \times 10^{-4} \quad \text{Im}(δ)=1.6 \times 10^{-5}

\begin{align*}
R_{2,\text{CPT}}^{\text{exp}} &= \frac{D_{\text{CPT}}^{\text{exp}}}{D_{\text{CPT}}} \\
R_{4,\text{CPT}}^{\text{exp}} &= \frac{D_{\text{CPT}}^{\text{exp}}}{D_{\text{CPT}}}
\end{align*}

Additional pros:
- contrarily to T violation, the effect $\propto \Re\delta$ does not vanish with $\Delta \Gamma \to 0$
- No assumption on CPT violation in semileptonic decays is needed

A. Di Domenico
Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with 
\[ \text{Re}(\delta) = 3.3 \times 10^{-4}, \text{Im}(\delta) = 1.6 \times 10^{-5} \]

\[ R_{2,\text{CPT}}^{\exp} / D_{\text{CPT}} \]
\[ \sim 0.1\% \text{ violation} \]

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- contrary to T violation, the effect \( \propto \Re \delta \) does not vanish with \( \Delta \Gamma \to 0 \)
- No assumption on CPT violation in semileptonic decays is needed
Search for CPTV and Lorentz invariance breaking

$$\delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \beta_k \cdot \Delta \vec{a} \right) / \Delta m$$

Data divided in 4 sidereal time bins x 2 angular bins

Simultaneous fit of the $\Delta t$ distributions to extract $\Delta a_{\mu}$ parameters
Search for CPTV and Lorentz invariance breaking

\[ \delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \beta_K \cdot \Delta \tilde{a} \right) / \Delta m \]

Data divided in 4 sidereal time bins x 2 angular bins
Simultaneous fit of the \( \Delta t \) distributions to extract \( \Delta a_\mu \) parameters

with \( L = 1.7 \text{ fb}^{-1} \) KLOE final result

**PLB 730 (2014) 89–94**

\[ \Delta a_0 = \left( -6.0 \pm 7.7_{\text{STAT}} \pm 3.1_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]
\[ \Delta a_X = \left( 0.9 \pm 1.5_{\text{STAT}} \pm 0.6_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]
\[ \Delta a_Y = \left( -2.0 \pm 1.5_{\text{STAT}} \pm 0.5_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]
\[ \Delta a_Z = \left( -3.1 \pm 1.7_{\text{STAT}} \pm 0.6_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]

These are the most precise measurements in the quark sector of Standard Model Extension
(Kostelecky PRD 61 (1999) 016002)

In B,D systems:
\( \sigma(\Delta a_\mu^{B,D}) \) is \( O(10^{-13}) \) GeV
\[ \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{CPT violation in entangled K states} \]

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator “ill-defined”) the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:


\[ |i\rangle \propto \left( |K^0\rangle|\bar{K}^0\rangle - |K^0\rangle|\bar{K}^0\rangle \right) + \omega \left( |K^0\rangle|\bar{K}^0\rangle + |K^0\rangle|\bar{K}^0\rangle \right) \]

\[ \propto \left( |K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle \right) + \omega \left( |K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle \right) \]

at most one expects:

\[ |\omega|^2 = O\left( \frac{E^2/M_{PLANCK}}{\Delta \Gamma} \right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3} \]

In some microscopic models of space-time foam arising from non-critical string theory:

\[ \omega \sim 10^{-4} \div 10^{-5} \]

[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]

**KLOE result**

**PLB 642 (2006) 315**

**Found. Phys. 40 (2010) 852**

\[ \Re \omega = \left( -1.6^{+3.0}_{-2.1}^{\text{STAT}} \pm 0.4^{\text{SYST}} \right) \times 10^{-4} \]

\[ \Im \omega = \left( -1.7^{+3.3}_{-3.0}^{\text{STAT}} \pm 1.2^{\text{SYST}} \right) \times 10^{-4} \]

\[ |\omega| < 1.0 \times 10^{-3} \text{ at 95\% C.L.} \]
**Φ → K_S K_L → π^+π^- π^+π^-**: CPT violation in entangled K states

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KLOE-2 goal \( \sigma(\omega) \sim O(10^{-5}) \)
New formulation of Bell’s inequality for neutral kaons

J. Bell himself considered to use entangled K\(^0\)'s to test BI !! (Varenna School, 1970)

\[
\min_{\text{all } \rho_{\text{sep}}} S(t_1, t_2, t_3, t_4) \rho_{\text{sep}} \leq S(t_1, t_2, t_3, t_4) \leq \max_{\text{all } \rho_{\text{sep}}} S(t_1, t_2, t_3, t_4) \rho_{\text{sep}}
\]

where:

\[
S(t_1, t_2, t_3, t_4) = E(t_1, t_2) - E(t_1, t_3) + E(t_4, t_2) + E(t_4, t_3)
\]

\[
E(t_1, t_2) = 1 + 4 P(K^0, t_1; K^0, t_2) - 2P(K^0, t_1; \ast) - 2P(\ast; K^0, t_2)
\]

In this example: \(t_1, t_2, t_3, t_4 \sim 5 \tau_S\)

**CP violation plays a crucial role in Bell’s inequality violation: CPV -> BIV**
Conclusions

• The next generation of experiments at hadron machines (NA62 and KOTO) are operational, allowing us to definitely enter the very rare kaon decay era.
• Data taking will be completed in 2-3 years from now.
• Ultra high sensitivity and precision will be essential and crucial as a probe of New Physics beyond the SM, and complementary to LHC.

• The KLOE-2 experiment at the upgraded DAFNE started taking data with the plan to collect $O(10) \text{ fb}^{-1}$ in the next 2-3 years.
• The connection of entanglement with discrete symmetries of neutral kaons is still surprising and will continue to be one of the key issues at KLOE-2 with several high precision Quantum Mechanics, CPT and T symmetries tests.

• Sometimes we are in very stormy seas....which requires great perseverance, tenacity and patience to achieve the results.